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Turbulent transport studies in JET edge plasmas in *X*-point configurations

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Abstract

Reciprocating Langmuir probe measurements were obtained in dedicated JET experiments to investigate turbulent transport at the edge and SOL plasmas. The measured turbulent radial particle flux, radial velocity and diffusion coefficient were compared with results from the 2-D plasma edge code B2-EIRENE. Qualitatively, the experimental results and the modelling calculations show a similar behaviour, with the radial particle flux increasing from inside the separatrix to some point in the SOL and then decreasing again. However, there is a quantitative disagreement between code calculations and measurements in *X*-point plasmas. Two explanations have been proposed to reconcile these observations: first temperature fluctuations, with the appropriate phase could modify the derived particle turbulent flux. Second, code simulations including the effect of drifts at the plasma edge show that large convective cells appear in this region, leading to large parallel flows in the SOL, which have been measured. Such drifts could lead to a net inwards particle pinch which could compensate for the measured large turbulent out flux. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Divertor; Modelling; Anomalous Transport

1. Introduction

Turbulent transport is normally regarded as the mechanism responsible for the anomalous edge transport in tokamaks. Most of the experimental observations that form the basis for such hypothesis come from experiments in which the plasma is limited by a material element (limiter configuration). For divertor discharges, it is assumed as well that turbulent transport is the driving mechanism of anomalous edge transport. However, there are characteristics of divertor discharges that could lead to significantly different transport mechanisms, such as the large magnetic shear at the edge and drifts associated with the gradients of plasma edge parameters.

In the work presented in this paper, reciprocating Langmuir probe measurements have been obtained in dedicated JET divertor experiments in order to investigate turbulent transport at the plasma edge. A comparison of the measurements with simulations from the 2-D plasma edge code B2-EIRENE [1] is described in Section 3.

2. Experimental results

The turbulent particle transport has been studied in the JET (gas-box pumped divertor [2]) plasma boundary with a Langmuir probe array system installed at a major

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radius of $R = 3.253$ m on the top of the machine. Measurements have been taken in Ohmic, L-mode and H-mode regimes. Comparable measurements have been obtained in limiter discharges [3], which allows the direct experimental comparison between *X*-point and limiter plasmas in JET.

To determine if the edge particle transport is dominated by anomalous turbulent diffusion, we compare $\Gamma_r = \langle \tilde{n}\tilde{E}_\theta \rangle / B_T$ ($\tilde{n}$ and $\tilde{E}_\theta$ are the fluctuations in density and poloidal electric field, respectively) across changes in confinement regimes. We normalize Γ_r to the local electron density, n_e, and this magnitude is equivalent to an effective radial velocity, v_{reff}, in the B2-EIRENE local transport analyses. Besides, this coefficient is not affected by the uncertainties in the probe area, as the relation: $v_{\mathrm{reff}} = \langle \tilde{I}_{\mathrm{sat}}\tilde{E}_\theta \rangle / I_{\mathrm{sat}} B_T$, where I_{sat} is the ion saturation current.

The profiles shown in Fig. 1 correspond to an ohmic plasma: #46 571 ($B_T = 1.4$ T, $I_P = 1.8$ MA and $\langle n_e \rangle = 1.5 \times 10^{19}$ m^{-3}). The position of the last closed flux surface (LCFS) is determined by magnetic equilibrium codes and their accuracy of about ±10 mm, at the outer mid-plane of JET.

Different fluctuating quantities are plotted in Fig. 1 versus the distance from the LCFS mapped at the probe position. Similar fluctuation levels have been obtained in other devices [4,5] and in JET limiter discharges [3]. The poloidal phase velocity of fluctuations (Fig. 1(c)) is not well defined far in the SOL and becomes negative (electron drift direction) close to the LCFS and into the edge of the main plasma. The radial position where this change occurs is called the velocity shear layer (VSL) [6]. In all the analysed cases in *X*-point configuration and in this particular shot (see Fig. 1(c)), the VSL seems to be about 1–2 cm outside the LCFS, into SOL region. On the other hand, the VSL in limiter plasmas has been localised around the limiter radial location (i.e., the LCFS) or into the edge of the main plasma [3]. That could be an indication of the different behaviour of the radial electric field in the SOL plasmas of limiter and *X*-point discharges in JET. The radial profile of the time averaged turbulent flux is shown in Fig. 1(d). The maximum of the flux is localised close to the LCFS. The maximum of the turbulent particle flux is about a factor 3–5 larger than in limiter magnetic configuration, for similar plasma parameters, which seems to be in contradiction with the plasma global particle confinement times. The radial profile of the effective radial velocity shows a slight maximum about the separatrix position (Fig. 1(e)), which is probably induced by the maximum in the turbulent particle flux.

The coherency and the phase between the fluctuations of E_θ and I_{sat} is critical for the estimation of the radial turbulent particle flux together with the density and poloidal electric field fluctuations. It has been found that the contribution of the low frequency range in those magnitudes dominates the turbulent flux in the SOL region. In contrast, the contributions from high frequencies become significant as the probe goes close to and inside the LCFS, while turbulent transport at low frequency in this region is almost negligible.

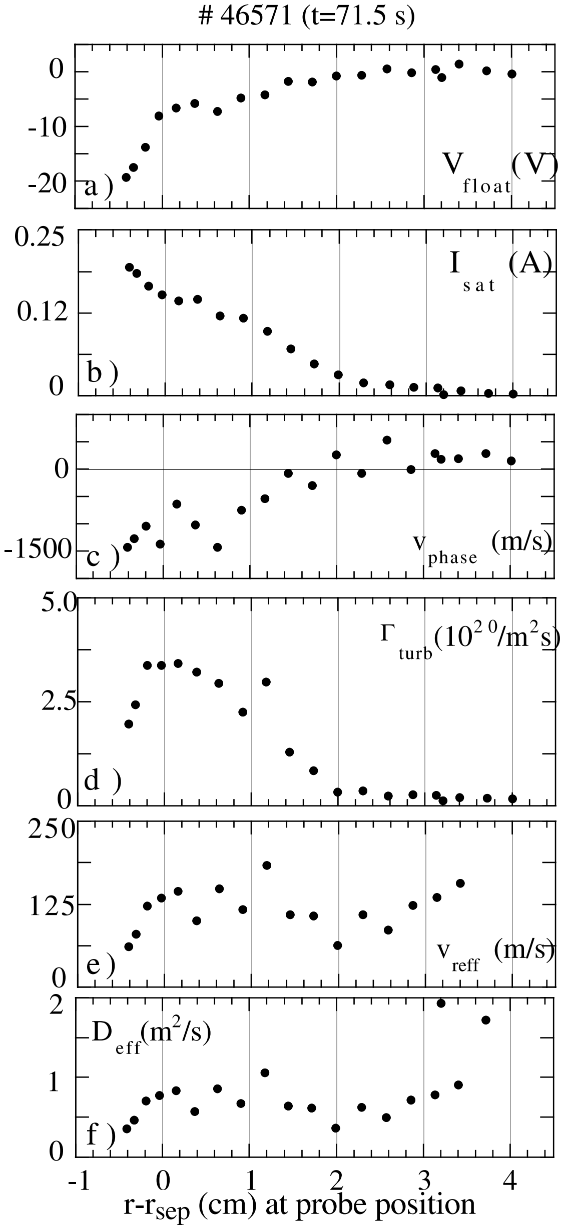

Fig. 1. Radial profile of floating voltage (a), ion saturation current (b), poloidal phase velocity of the fluctuations (c), $E \times B$ turbulent particle flux (d), radial effective velocity (e), diffusion coefficient from turbulent measurements (f).

Turbulent particle flux measurements were also carried out in plasmas with different levels of NBI heating power, in order to determine whether or not there are any trends with heating power in the characteristics of the turbulence. The shot considered here features a power scan (from 1 to 5 MW of NBI) during which the global plasma parameters are kept constant: #46 576 ($I_P = 2.8$ MA, $B_T = 3$ T and $\langle n_e \rangle = 3.5 \times 10^{19} \mathrm{m}^{-3}$). Fig. 2 shows the radial profile of the turbulent flux (Fig. 2(a)), the density normalised fluctuation levels (Fig. 2(b)) and the effective radial velocity calculated from the turbulent fluxes (Fig. 2(c)) for three different NBI heating levels: 1, 2 and 5 MW. The measured density decay length is about 0.7 cm at the outer mid-plane in the three cases. The D_{perp} calculated from this measurement does not show any trend with power, and its value is about 1 $\mathrm{m}^2\ \mathrm{s}^{-1}$ at the LCFS position, which is one order of magnitude larger than the D_{perp} expected from code simulations. The conclusion extracted from this preliminary analysis is that no significant differences in turbulent transport in L-mode SOL plasmas with different NBI heating have been observed.

The comparison of the turbulence behaviour between an ohmic plasma, #46 580 ($I_P = 1.3$ MA, $B_T = 1$ T and $\langle n_e \rangle = 1.5 \times 10^{19}\ \mathrm{m}^{-3}$) and an H-mode plasma, #46 584 ($I_P = 0.9$ MA, $B_T = 1$ T and $\langle n_e \rangle = 3.5 \times 10^{19}\ \mathrm{m}^{-3}$) is shown in Fig. 3. The data in H-mode have been taken between ELMs, with the time of the measurements more than 50 ms apart from the nearest ELM. Strong changes in the edge profiles and turbulent transport parameters have been found between these two plasma regimes. The I_{sat} profile (Fig. 3(a)) steepens substantially and the poloidal phase velocity of the fluctuations (Fig. 3(b)) indicates a stronger radial electric field in H-mode. The turbulent fluxes are reduced at the probe position by at least one order of magnitude in H-mode, relative to the ohmic plasmas (Fig. 3(d)) and a dramatic reduction of the effective diffusion coefficient by more of an order of magnitude has been found in the SOL plasma close to the LCFS (Fig. 3(e)).

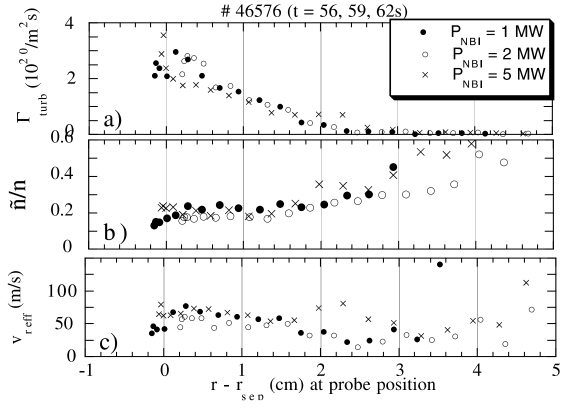

Fig. 2. Radial profile of turbulent flux (a), normalised density fluctuations (b) and radial effective velocity (c) for three NBI heating powers 1, 2 and 5 MW.

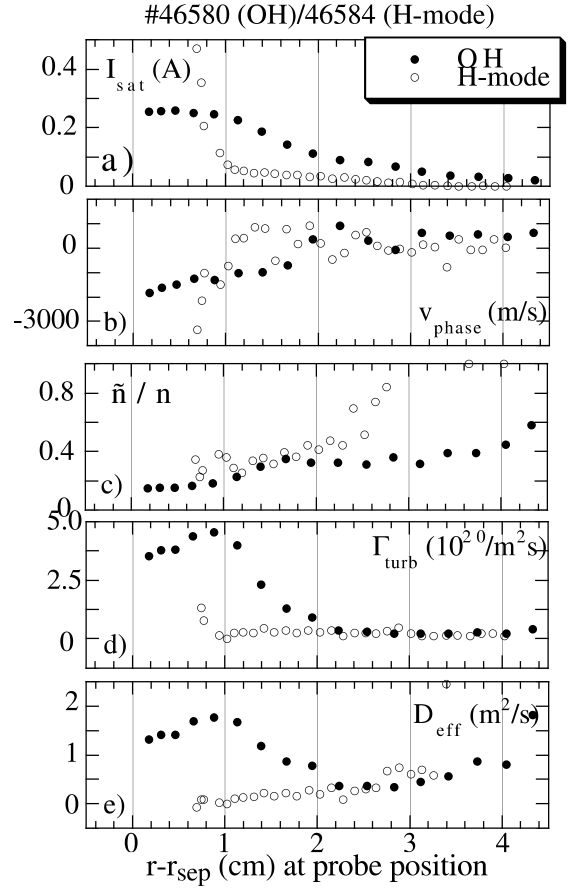

Fig. 3. Radial profile of ion saturation current (a), poloidal phase velocity (b), normalised fluctuation levels of density (c), turbulent particle flux (d) and effective diffusion coefficient (e) for ohmic and H-mode plasmas.

As it is observed in limiter discharges in JET [3] and in other experiments [7], the analysis of the floating potential fluctuation spectra for divertor discharges in JET shows the existence of three distinct fluctuation ranges as well. In each of these ranges, and in the absence of MHD activity, the spectrum is well described by an algebraic function. In the lowest frequency range, the spectral decay index seems to be independent of the frequency and the spectrum is basically flat. In the highest frequency range, the spectral decay index is of the order of −2 or even higher. In the intermediate frequency range, the spectral decay index is around −1, once the Doppler shift effects induced by the plasma velocity have been taken into account. It is interesting to note that the frequency region where the spectrum shows a decay index close to −1 corresponds to the frequency range where the turbulent particle flux spectral function is maximum. That is valid both for the SOL and for the edge of the main plasma. In the framework of self-organised criticality models (SOC), this $1/f$ behaviour arises from the existence and random superposition of avalanches [7].

3. B2-Eirene modelling

B2-EIRENE modelling for typical JET-gas-box Plasma conditions were carried out in order to compare the modelled anomalous fluxes with the measurements. In the absence of turbulence measurements, the transport coefficients used in the modelling are determined by the decay length of the temperature and density profiles at the reciprocating probe position in JET. In the simulations presented here, four models that produce a density profile with typical decay length of ~1 cm have been tested. Model 1 assumes that particle transport at the plasma edge is characterised by a constant diffusion coefficient of 0.1 $\mathrm{m}^2\ \mathrm{s}^{-1}$. Model 2 assumes that transport at the edge is characterised by a constant diffusion coefficient of 0.3 $\mathrm{m}^2\ \mathrm{s}^{-1}$ and an inwards pinch velocity of 5 m s^{-1}. Model 3 assumes an Alcator-like scaling of the diffusion coefficient at the plasma edge with density. Model 4 assumes a Bohm-like dependence of the diffusion coefficient at the plasma edge and Model 1B is similar to Model 1 but assumes a radial increase of the transport coefficient in the SOL with distance to the separatrix. The diffusion coefficient profiles for these models are shown in Fig. 4(a).

In the vicinity of the separatrix, all modelled density profiles are similar despite the different transport assumptions. This indicates that transport phenomena along the filed line have a deep influence in determining the shape of the density profiles in the SOL of JET-gas-box discharges. The corresponding anomalous fluxes driven by the different transport models are given in Fig. 4(b). All show an increase of the perpendicular flux when moving from the plasma into the SOL with a maximum located typically at 5–8 mm from the separatrix at the mid-plane. The anomalous flux decays with distance from the separatrix in the SOL. The shape of the modelled profiles shows the same qualitative trends as the experimental measurements but the values of the modelled anomalous flux are typically an order of magnitude lower than the measured turbulent fluxes.

A comparison of the anomalous velocity obtained with different models shows that the values in the vicinity of the separatrix are typically an order of magnitude smaller than the measurements in the same way as the anomalous particle fluxes. The shape of the velocity profiles is very transport model dependent.

The disagreement between the measured and calculated fluxes in the SOL indicates the existence of complex particle transport phenomena in the SOL of diverted discharges and/or questions the diffusive nature of the SOL particle transport. There is evidence that large parallel flows exist in the SOL of JET-gas-box diverted discharges [8]. Such flows can create large convective cells in the SOL, so that parallel transport along the field can be significantly different from the modelling calculations presented here (without drifts) and this, in turn, can influence anomalous perpendicular transport. Comparisons of the predicted trends for the modelled anomalous velocity and the measured one, together with the SOL density thickness and detachment behaviour, could be used to determine the transport model which describes best the JET SOL plasmas in diverted discharges following the approach presented here.

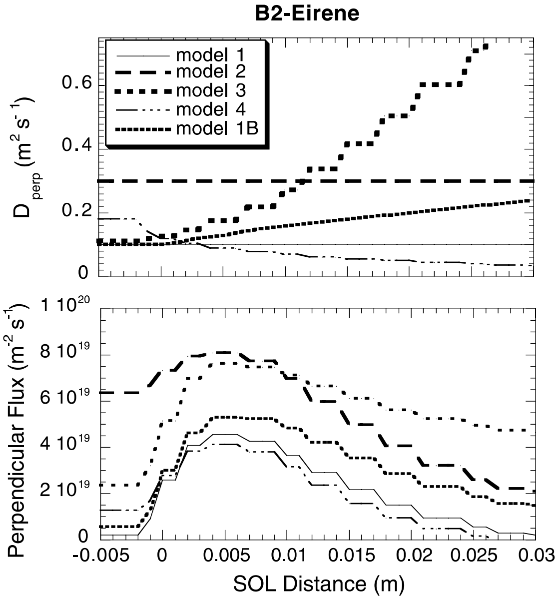

Fig. 4. Radial profiles of the diffusion coefficient (a) and calculated anomalous fluxes (b) for the different models.

4. Summary

Differences in the profiles of the poloidal phase velocity between limiter and *X*-point discharges indicate that the radial electric field has a different origin for these two magnetic configurations. Furthermore, the turbulent particle flux in divertor plasmas is about a factor 3–5 larger than in similar limiter plasmas, in conflict with the plasma global particle and energy confinement times.

The measured turbulent radial particle flux, radial velocity and diffusion coefficient have been compared with results from calculations with the 2-D plasma edge code B2-Eirene. Qualitatively, the experimental results and the modelling calculations show a similar behaviour with the radial particle flux increasing from inside the separatrix to some point in the SOL (close to the separatrix) and then decreasing again. However, there is a large quantitative disagreement between code calculations and measurements.

Different explanations have been proposed to reconcile these observations. First, temperature fluctuations (not measured in JET) with the appropriate phase could modify substantially the derived particle turbulent flux, although no evidence for that exists from other machines. Second, a diffusive model might not be adequate to describe particle transport in divertor plasmas. In particular, code simulations that include the effect of drifts at the plasma edge show that large convective cells can appear in this region leading to large parallel flows in the SOL, which have been measured. Such drifts could lead to a net particle pinch, which could compensate for the measured large turbulent flux. On the other hand, the possible role of large-scale transport events (i.e., SOC models), as a mechanism connecting the edge and core regions, should be considered to explain the bursty behaviour of turbulent transport and the $1/f$ feature, for a given range of frequencies, in the flux spectrum. The investigation of the dynamic interplay between fluctuations in gradients and $E \times B$ turbulent fluxes might help to test the importance of diffusive versus SOC transport mechanisms.

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